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Cost benefit analysis of dynamic route planning at sea

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Abstract

Route optimization through dynamic route planning, where ships can shorten their routes taking other vessels movements into account through shared information, has a potential to make transportation at sea more efficient. Fuel and emissions can be saved through green steaming without increased cargo transit times, and without reducing safety. This study estimates the potential net benefits to society in major areas in the Baltic Sea and the North Sea. It is found plausible that routes can be shortened by one percent on average, which would reduce costs to society by 80 million euros per year, of which 35 percent are reduced fuel costs and 65 percent are reduced emission costs. Alternative unit values of emissions give an interval of 55 to 113 million euros in benefits. The project's costs are estimated at 15 million euros per year. With a growing world trade, the potential for more efficient and environmentally friendly sea transportation through dynamic route planning may be substantial.

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Keywords: sea transportation; cost benefit analysis; route optimization; emissions; environment; efficiency

1. Introduction

Rapidly growing international trade together with the intention to reduce global emissions leads to increasing needs to make transportation at sea more efficient. Lower fuel consumption and transportation emissions can be achieved by decreasing speed (Fagerholt et al., 2010, Chang and Chang, 2013, Maloni et al., 2013). A negative

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effect of slower speed is increased container transit time (Yin et al., 2014). The International Maritime Organization proposed larger vessels, reduced speed, and new technologies to reduce greenhouse gas emissions (Woo and Moon, 2014). However, such measures to lower emissions will come at the cost of increased capital expenditure (Hoffmann et al., 2012). Sea Traffic Management (STM) is a concept developed within the MONALISA project, which is aimed at increasing safety, environmental and operational efficiency for sea transportation. (Lind et al, 2014). One part of STM is Dynamic Route Planning (DRP) based on updated information about the intended routes of vessels in the area and shared information. This will create a potential for ships to take shorter routes, save fuel and reduce the impact on the environment without increasing the cargo transit time.

In this paper, the potential savings of fuel and emissions from route optimisation are analysed. We assume that safety remains unchanged, although another study in the project indicates positive effects also on safety through fewer possible conflicts between ships (SSPA, 2015). The availability of data from ships' AIS-transmitters provides new opportunities to quantify sea traffic and evaluate proposals aimed to make sea transportation more efficient. The volume of sea traffic for two major areas in the North Sea and in the Baltic Sea is calculated, based on complete AIS-data for three selected days. Then, the total costs of the traffic are estimated by using formulas for fuel consumption and emissions together with unit values for fuel and emissions. Together with AIS-data from passage lines and results from simulations made in other studies, this will provide a base for the estimation of the potential for savings by allowing sailing shorter routes.

The benefits will be compared to estimated costs for developing technology and investments in equipment as well as for training and for running the system. Monitoring and governance may be necessary. We analyse the potential net gains for society as a whole, by estimating the benefits and costs of implementing DRP using Cost--Benefit Analysis (Boardman et. al, 2010). By society, all parties that in one way or another are affected by sea transportation are included, i.e. both the buyers and sellers of the services and the rest of society.

2. Estimating costs for fuel and emissions of sea transportation

The fuel consumption by a ship is mainly affected by size, type, condition of ship, speed and load. Emissions are affected by fuel consumption as well as type of engine, presence of catalyser and fuel type (SEPA, 2010).

2.1. Fuel costs

The model for hull resistance in deep water (Larsson, Raven, 2010), applied by the Swedish maritime research institute SSPA (Holm, 2015), is used to estimate fuel consumption for the ships in the study. Fuel consumption for a specific journey by a ship is calculated as:

$$C = \frac{R_T * D}{E_{MGO} * \eta_T} \tag{1}$$

where
C = fuel consumption in kilogram
R_T = resistance
D = sailed distance in meters
E_{MGO} = MGO (Marine Gas Oil) energy density, 46200 is used
η_T = overall efficiency, 0.35 is used

$$R_T = \frac{1}{2} * \rho * V_S^2 * (B + 2d) * L * C_B * C_{TS} \tag{2}$$

where
ρ = water density, 1.25 is used
V_S = velocity (speed) in m/s
B = beam of vessel
DR = draught of vessel

L = length of vessel
C_b = block coefficient measuring size of hull
C_{TS} = resistance constant, 0.0022 is used

D, VS, B, DR and L are taken from each ship's AIS-data. Cb differs by ship type (Tupper 2013:37)[1]. The water density factor is used to adjust for the impact of wind and waves (Nabergoj and Prpic-Orsic, 2007, Szelangiewicz et al, 2014).

To calculate fuel costs, the price of fuel is multiplied with the consumption in kilogram. All vessels in the studied area are assumed to use Marine Gas Oil (MGO), as regulated by the European Union (EU, 2012). The Sulphur Emission Control Area (SECA) includes the Baltic Sea, the North Sea and the English Channel. The limit of sulphur for all bunker oil on board ships is set at a maximum of 0.10% in the SECA area from 1 January 2015.

The price of MGO in Rotterdam on the base date, June 15, 2015, was 553.5 USD/metric ton (Bunkerindex, 2015). However, the price fluctuates substantially. In a sensitivity analysis, the average price for the studied three days, 623.7 USD/ton, and, as spot prices have fallen substantially during 2014–15, a 50 percent higher spot price is used as alternatives.

2.2. Emission costs

For emissions of CO_2 the constant according to Wang (2010) is used:

$$CO_2 = 3.13*C \tag{3}$$

When we calculate emissions of nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter 2.5 ($PM_{2.5}$), the emissions per kg fuel for different categories in SEPA (2010) are applied. Table 2.1 shows emissions of NO_x, SO_2, and $PM_{2.5}$ per kg fuel, assuming that all ships are driven by MGO with sulphur content of maximum 0.1%.

Table 1. Kg emissions of NO_x, SO_2 and $PM_{2.5}$ per kg fuel, categories of ships.

Ship type	NO_x	SO_2	$PM_{2.5}$
Cargo small	0.0731	0.00180	0.00119
Bulk medium	0.0728	0.00170	0.00115
Bulk large	0.0729	0.00172	0.00116
RoRo (incl automobile)	0.0661	0.00191	0.00125
Container medium	0.0733	0.00184	0.00122
Container large	0.0733	0.00184	0.00122
Container very large	0.0722	0.00156	0.00108
Tanker small	0.0731	0.00180	0.00119
Tanker medium	0.0728	0.00170	0.00115
Tanker large	0.0734	0.00181	0.00134
Tanker very large	0.0734	0.00181	0.00134

Source: Table 12, SEPA (2010), adjusted for shifting to MGO.

There are different recommendations of which unit values that should be used for cost-benefit analysis in the transport sector, and calculations are based on a couple of different recommendations within the EU. ASEK is a project in Sweden, led by the Swedish Transport Administration that, based on research, recommends which

[1] 0.75 is used for general cargo, 0.8 for bulk, small and medium tankers, 0.67 for all container and RoRo ships, and 0.85 for large and very large tankers.

methods and unit values that should be used for cost-benefit analysis in the transport sector in Sweden. We use values recommended by ASEK 5 (The Swedish Transport Administration, 2014) as well as values from the European Union's program for clean air called Clean Air for Europe (CAFE) (EC DG Environment, 2005). For CO_2, values from the Stern Review on the Economics of Climate Change (Stern, 2006) that discusses the effects on the world economy of global warming, and the prise of carbon dioxide in the EU Emissions Trading System (EU ETS) are also used as alternatives. Concerning emissions of carbon dioxide, the costs are globally distributed and the same value for the Baltic Sea and the North Sea is used. The values recommended by ASEK are shown in Table 2.

Table 2. Values euros/kg ASEK, price level 2015.

Emission	Area	Value
CO_2		0.12
NO_X	Baltic Sea	9.01
SO_2	Baltic Sea	3.04
$PM_{2.5}$		-

Source: ASEK (2014).

ASEK has neither estimated values for $PM_{2.5}$ nor any specific values for the North Sea, so we will use the same figures for both areas for NO_X and SO_2. Table 3 shows the values in CAFE in 2015 price level.

Table 3. Values euro/kg CAFE, price level 2015[2].

Emission	Area	CAFE 1	CAFE 2	CAFE 3	CAFE 4
CO_2		-	-	-	-
NO_X	Baltic Sea	3.16	4.86	5.95	8.75
	North Sea	6.19	9.60	11.54	17.01
SO_2	Baltic Sea	4.49	7.05	8.99	13.36
	North Sea	8.38	13.36	17.01	24.29
$PM_{2.5}$	Baltic Sea	14.58	23.08	29.15	42.51
	North Sea	34.01	51.02	65.59	97.18

Source: EC DG Environment (2005).

CAFE has not estimated any values for CO_2. Table 4 shows the values for CO_2 by Stern and the price of emission allowances in EU ETS in June 2015.

Table 4. Values euro/kg Stern and EU ETS, price level 2015.

	Stern Low	Stern High	EU ETS
CO_2	0.07	0.28	0.008

Source: Stern (2006), EU ETS (2015)

3. Volume and costs for traffic in the studied areas

In this study, the traffic is quantified using Automatic Identification System (AIS) data from vessels in the Baltic Sea and in the North Sea. It is mandatory since 2007 for commercial vessels to have an AIS transmitter that

[2] The four scenarios in CAFE differ in respect to the method to value mortality, the sensitivity to the range of effects included and the impact on ozone. Values are higher for the North Sea than for the Baltic Sea because larger populated areas are affected by the emissions.

continuously sends a signal with information about the ship (EU Directive 2013/52/EU). Depending on the ship's speed, a signal is registered with different frequencies, and a single ship's position and other data can be registered and result in over 1,000 observations in one day. This data is made available via the Swedish Maritime Administration: the data from the selected area in the Baltic Sea are gathered by the HELCOM member states, while the data from the selected area in the North Sea consists of data which are gathered by Danish authorities. No AIS data for the rest of the North Sea or the Mediterranean Sea is available by the Swedish Maritime Administration. See the shaded area in figure 3.1 below for the exact picture of the selected areas.

The chosen days are September 1, 2014; February 4, 2015, and April 10, 2015 when there was no ice, strong wind or waves that could cause delays for the ships in the selected areas. Moreover, the study is confined to ships supposed to be mainly affected by DRP: 'cargo' (including general cargo, bulk, ro-ro, automobile carriers, and container) or 'tanker'. Ships below 60 meters and 300 GT are excluded from the study.

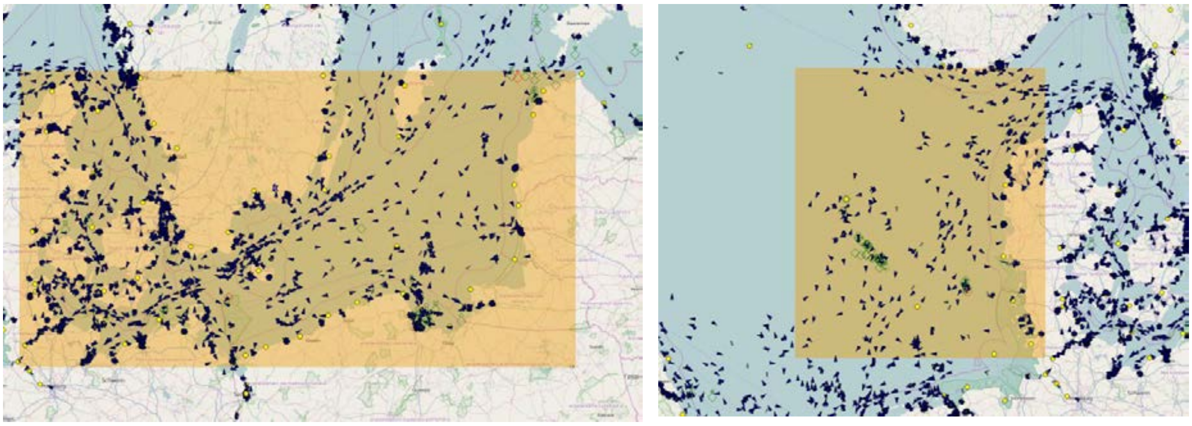

Fig. 1. (a) studied area in the Baltic Sea; (b) studied area in the North Sea.

For each ship, the average speed from all observations during the time that the ship was sailing is calculated, and subsequently multiplied with the total time, to obtain sailed distance. Observations when the ships' speed was below one knot are excluded, as this may be maneuvering in a port or moving while lying along a berth or at anchor. Information about each vessel's GT as well as the type of cargo ship: general cargo, container, roro/automobile carrier or bulk is gathered at the website MarineTraffic (2015) and categorized in 11 types of ships, based on SEPA (2010), see Table 5[3].

3.1. Volume of traffic

There were in total 1,944 observed ship voyages in the Baltic Sea and 1,111 in the North Sea at the studied three days. The ships are ordered in categories for which we have some of the cost data. The distribution between cargo vessels and tankers is almost the same in both areas: about 75 percent are cargo vessels and 25 percent tankers. In the Baltic Sea, 53 percent of the ships are below 6,000 GT and in the North Sea 44 percent is below 6,000 GT.

[3] To present a more comprehensive picture of the composition of ships, the "very large" categories were added to the ones used by SEPA. Their categories are constructed to represent the traffic around Sweden, where very large ships are uncommon.

Table 5. Number of ship voyages of each ship type in the study.

	Ship type	GT	Baltic Sea		North Sea	
cargo	Cargo small	300–5,999	843	43.3%	393	35.3%
	Bulk medium	6,000–13,999	98	5.0%	68	6.1%
	Bulk large	14,000–	167	9.1%	143	12.8%
	RoRo (incl automobile)	6,000–	113	5.8%	68	6.1%
	Container medium	6,000–13,999	129	6.6%	66	5.9%
	Container large	14,000–69,999	92	4.7%	70	6.3%
	Container very large	70,000–	7	0.4%	34	3.0%
tanker	Tanker small	300–5,999	181	9.3%	98	8.8%
	Tanker medium	6,000–13,999	64	3.3%	45	4.1%
	Tanker large	14,000–69,999	242	12.4%	114	10.3%
	Tanker very large	70,000–	8	0.4%	13	1.2%
	Total		1,944		1,111	

3.2. Costs for the traffic

The unit costs presented in chapter 2 are applied to the ships observed during the three days and multiplied with 120 to obtain estimates for a whole year. The cost for fuel depends largely on the current fuel price, which fluctuates significantly. In addition to the spot price, two alternatives with the average price of the three studied days, 624 USD/ton, and a 50 percent higher spot price are also calculated[4]. The results are shown in Table 6.

Table 6. Annual fuel costs for the traffic in the Baltic Sea and North Sea areas, million EUR.

	Spot price June 15	Average spot price the 3 studied days	50% higher spot price
Baltic Sea	522.2	588.4	783.3
North Sea	418.3	471.4	627.5
Total	940.5	1,059.8	1,410.8

Total costs using the spot price in June are near 1 milliard euros, and even more if the alternative fuel prices are used. In addition are the costs for society from emissions. Table 7 and 8 show emission costs calculated with the different unit values presented in Chapter 2, as well as an average of the different values.

Table 7. Annual costs for emissions of CO_2 for the traffic in the Baltic Sea and North Sea areas, million EUR.

	ASEK	Stern low	Stern high	EU ETS	Average[5]
Baltic Sea	316.4	184.6	738.2	21.1	413.1
North Sea	253.5	147.9	591.4	16.9	330.9
Total	569.8	332.4	1,329.7	38.0	744.0

[4] Values in USD have been converted into euros with the exchange rate 1.12 USD/EUR as of June 15, 2015.

[5] For emissions of CO_2, the values from EU ETS were not included in the average. If EU ETS is included, the average will fall with 25 percent to 559 million EUR.

Table 8. Annual costs for emissions of NO_X, SO_2 and $PM_{2.5}$ for the traffic in the Baltic Sea and North Sea areas, million EUR.

	ASEK	CAFE 1	CAFE 2	CAFE 3	CAFE 4	Average
Baltic Sea NO_X	549.6	194.6	299.3	366.4	538.8	390.8
North Sea NO_X	431.7	296.6	459.9	552.9	815.0	511.2
TOTAL NO_X	981.3	491.2	759.2	919.3	1,353.8	902.0
Baltic Sea SO_2	4.6	6.8	10.7	13.6	20.2	11.2
North Sea SO_2	3.7	10.2	16.2	20.7	28.3	15.8
Total SO_2	8.3	17.0	26.9	34.3	48.5	27.0
Baltic Sea $PM_{2.5}$	-	14.7	23.3	29.4	43.0	27.6
North Sea $PM_{2.5}$	-	27.5	41.3	53.1	78.7	50.2
Total $PM_{2.5}$	-	42.2	64.6	82.6	121.7	77.9

In Table 9 the costs for fuel and emissions for the traffic in the studied areas are summed up, using the emission costs based on the average figures given above.

Table 9. Total annual costs for sea traffic in the Baltic Sea and North Sea areas, million EUR.

	Fuel	CO_2	NO_X	SO_2	$PM_{2.5}$	Total
Baltic Sea	522.2	413.1	390.8	11.2	27.6	1,364.9
North Sea	418.3	330.9	511.2	15.8	50.2	1,326.5
Total	940.5	744.0	902.0	27.0	77.9	2,691.4

The total cost to society for fuel and emissions for the traffic in the studied areas is around 2.7 milliard euros per year when using the average unit values. Fuel costs are 35 percent and the remaining part are environmental costs. If instead the average fuel price for the three days is used, the share of fuel costs is 38 percent, and if fuel prices are assumed to be 50 percent higher, fuel costs would be 45 percent and the total cost 17 percent higher. As can be seen in Tables 3.3 and 3.4, the results largely depend on which unit values for emissions that are used. If the lowest values for emissions are used, except EU ETS, the total cost to society would be 32 percent lower and with the highest values 41 percent higher.

4. Cost-benefit analysis of dynamic route planning

4.1. The potential of sailing shorter distances

Ships might sail straighter courses in areas where the traffic today is taking longer routes that could be made more optimal through DRP. Routes can be shortened in situations when there is no conflicting traffic in separated zones, adjust more optimally to other vessels intended routes or through cutting corners of fairways. Today, traffic in opposite direction is typically separated by 7–10 kilometres in open waters. However, in narrow waters around Scandinavia and in fairways, the required separation is much less than in open waters. Applying DRP could ease the need to strictly follow the separated zones in areas with dense traffic.

To obtain an indication of the possible gains, the Swedish Maritime Administration delivered AIS data from passage lines in the southern part of the Baltic Sea for April 2015. Data of the inbound traffic that today takes a 5–7 percent longer route than the outbound traffic due to traffic separation has been analysed. Two passage lines were drawn for the incoming traffic to the Baltic Sea: one in the Strait of Öresund and one in Bälten. Another one was drawn northbound from the island of Bornholm to Sweden, ‘Bornholmsgattet’. Ships that passed through one of the first two lines and subsequently the second one were identified as ships that with optimized routes, monitoring and more flexible application of traffic separation could sail shorter distance. The distance from Öresund to Bormholmsgattet is approximately 70 NM and there were 24.6 ships per day on average. From Bälten to Bornholmsgattet, ships sail about 180 NM and there were 6.5 ships per day. Traffic along those two routes amounted to 3.8 percent of all ships and 3.5 of the sailed distance in the Baltic Sea area that is studied. If this traffic could take a five percent shorter route without reducing safety, 0.2 percent of the total cost would be saved.

SSPA (2015) have made simulations of the traffic in Kattegat, and the potential for optimized routes and resulting effects on safety. In one month, fuel consumption could be lowered by 10.8 percent. At the same time, with route optimization, the number of situations where ships come into conflicting courses could be reduced by over 50 percent compared to today. This case study is made in an area with heavy traffic and many conflicting ships, but nevertheless indicates that it is possible to shorten routes while simultaneously increasing safety.

In the cost-benefit analysis, it will be assumed that the average shortening of sailed distance for all vessels in the Baltic Sea and the North Sea is one percent. This will occur as a mix between vessels that already sail the shortest distance saving nothing, and vessels that can save more than one percent as described above. Thus, in the following, we will assume an overall potential for DRP to shorten routes by one percent without compromising on safety.

4.2. Project costs

As the required technologies and organisation for implementing DRM are still in a development phase, related costs have to be estimated based on current knowledge and reasonable assumptions. The figures presented in this section are best estimates given by relevant partners involved in the MONALISA project, and in order not to underestimate costs, a high alternative is used. As DRM can be implemented in a larger area than the one studied, only 50 percent of the non-area specific investments has been added to the costs.

Ships have to make investments in the technology required and also in training for the staff who are going to run the equipment. It is estimated that the annual costs for a vessel's required equipment for participating is 1,500 euros. In 2013 around 5,000 unique ships sailed in the Baltic Sea (Swedish Institute for the Marine Environment, 2014). Most ships in the Baltic Sea will also sail in the North Sea during a year. Half of this investment is allocated to the project, resulting in an investment cost of about 3.75 million euros per year.

Designated persons on-board will require training. On average, six persons per vessel are assumed to be involved in the procedures and training is estimated at 500 to 1,000 euros per person for a course including transportation. For the 5,000 ships in the area, the total cost is 30 million euros, which results in an annual cost of 1.5 million euros, if the average is used, when distributed over a ten-year period with a discount rate of 3.5 percent.

Ships applying DRM will incur communication costs for the information exchanged with other ships and monitoring centrals. The annual cost for this communication is estimated at on average 2,300 euros per ship and year. Our study finds on average 648 ships in the Baltic Sea and 371 ones in the North Sea per day. The annual communication cost including other ships like ferries, adding to 1,100 ships, is about 2.5 million euros.

To obtain the gains of route optimization monitoring centrals might be necessary, similar to an extension of existing VTS centrals for the open sea. Seven such centrals are assumed: five in the Baltic Sea and two in the North Sea. It is estimated that each central would invest 125,000 euros per year for equipment and hire seven employees per monitoring position. The labour cost per person in VTS functions is estimated to be 60,000 euros. It is assumed that each monitoring central has two positions. The annual cost for monitoring will be about 5.1 million euros per year. However, modern technology may ease the workload for VTS operators, and in the future it may be possible to monitor ships in open waters without increasing the number of operators. Finally, the entire system, whether confined to the EU or larger international areas will require some governing institution. As our study concerns a limited part of the European seas, it is assumed that governance costs will end at 2.5 million. The total costs for DRM will with the above assumptions sum up to about 15 million euros per year, of which 5 million are related to monitoring.

4.3. Cost-benefit analysis

The benefits of DRM from shorter routes can either be obtained by reducing speed and arriving at the same time as without DRP or by sailing at the same speed and arrive earlier to the next port. Ship owners will choose the most profitable alternative.

Formula (1) and (2) can be used to calculate the savings in fuel if distance decreases with 1% and speed decreases with 1%.

Let $\left(\frac{1}{2} * P * (B + 2d) * L * C_B * C_{TS}\right) = A$, and $(E_{MGO} * \eta_T) = B$ (4)

$$lnC = lnA + 2lnV_s + lnD - lnB \quad (5)$$

For marginal changes of speed (V_s) and sailed distance (D):

$$\frac{dlnC}{dlnV_s} = 2\%; \frac{dlnC}{dlnD} = 1\% \quad (6)$$

$$(1 - 0.98 * 0.99) = 0.0298$$

It follows that if a ship owing to DRP can sail one percent shorter distance, and thereby reduce speed by one percent, the marginal reduction in fuel consumption is 2.98 percent. By sailing at one percent slower speed, the ship owners would save 28 million euros per year in fuel costs. As emissions would be reduced by the same percentage, the total gain to society would be 80.2 million euros, using the given average values for emissions. This gives a benefit-cost ratio of (80.2/15) = 5.3. If all low values for emission are used instead of the average, the benefit would drop to 54.1 million with a ratio of 3.6 and the project is still estimated to be highly profitable. Applying all high unit values would give benefits of 113.1 and a ratio of 7.5.

In this study it is assumed that the benefits will be achieved through reduced speed. However, today contracts in the industry often stipulate that a ship should arrive as soon as possible. There is also transportation of high-value goods or other reasons why ships decide to arrive earlier instead of sailing slower. Another study (Andersson and Ivehammar, 2014) showed that the benefits to society when choosing earlier arrival is only 1/3 of the benefit by reduced speed, transit value of goods unaccounted for. Ship owners alone would gain about 40 percent by reducing speed instead of arriving earlier. Most of the benefits will occur as reduced emissions, but already with the spot price in the base case, the savings in fuel would be higher than all estimated costs for the project. With a higher fuel price, the project's profitability increases as the savings become 17 percent higher.

5. Conclusions

Sea transportation is in rapid growth due to the expansion of world trade, and consumes large amounts of resources and generates emissions to the environment. Route optimization through dynamic route planning where ships can alter their routes taking other vessels movements into account through shared information and possibly monitoring has a large potential to make transportation more efficient while not compromising on safety. This study has estimated the potential net benefits to society in the Baltic Sea and the North Sea. An average shortening of routes by one percent is considered plausible, which would reduce the costs to society by 80 million euros per year, of which 35 percent are fuel and the rest emissions. Alternative unit values of emissions give an interval of 55 to 113 million euros. The project's costs are estimated at 15 million euros per year. Regardless of which assumptions are made, route optimization has a positive net benefit to society.

If the average distance is shortened with 0.2 percent, the project is profitable from society's point of view, as the benefits then will be just more than the estimated cost of 15 million. However, as the ship owners only save on fuel, it is required at least a 0.65 percent reduction in the average distance to make it profitable for them to take the costs, provided that they should cover the full costs of the project including monitoring and governance.

To validate the conclusions, extended studies with longer time periods and more areas are needed. The design of the system and the related costs has to be made more precise. More simulations of the potential to optimize routes and more research on the effects of emissions to better estimate their unit values. Sea transportation is essential to global trade and welfare, but simultaneously an important source of emissions and fuel consumption. This study indicates that dynamic route planning has a great potential to save resources without increasing the transit time of cargo.

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